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# **Experimental Investigation of a Variable Speed Constant Frequency Electric Generating System from a Utility Perspective**

J I Herrera, T.W Reddoch,  
and J S. Lawler  
Electrotek Concepts, Inc

**May 1985**

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Lewis Research Center  
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for  
**U.S. DEPARTMENT OF ENERGY  
Conservation and Renewable Energy  
Wind Energy Technology Division**



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J.I. Herrera, T.W. Reddoch,  
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Knoxville, Tennessee 37902

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## CONTENTS

<u>Section</u>	<u>Page</u>
1.0 INTRODUCTION . . . . .	3
2.0 WT SYSTEM DESCRIPTION . . . . .	5
2.1 Turbine Control System . . . . .	7
2.2 Generator Systems . . . . .	8
2.2.1 Induction Generator . . . . .	9
2.2.2 VSCF System . . . . .	10
3.0 TEST OBJECTIVES . . . . .	15
4.0 POWER QUALITY TESTS . . . . .	16
4.1 Test Procedure . . . . .	16
4.2 Test Results . . . . .	17
4.2.1 Harmonic Test Results . . . . .	17
4.2.2 Power Oscillation Test Results . . . . .	21
5.0 VOLTAGE/VAR MANAGEMENT . . . . .	25
5.1 Test Procedure . . . . .	25
5.2 Test Results . . . . .	26
5.3 Power Step Tests Under Constant Reactive Power Demand . . . . .	30
5.4 Voltage-Step Tests Under Constant Power and Power Factor . . . . .	32
6.0 TRANSIENT STABILITY TESTS . . . . .	37
6.1 Test Procedure . . . . .	37
6.2 Test Results . . . . .	38
7.0 CONCLUSIONS . . . . .	45
8.0 REFERENCES . . . . .	47

## SUMMARY

As efforts are accelerated to improve the overall capability and performance of wind-electric systems, increased attention on variable speed configurations has developed. A number of potentially viable configurations have emerged. Various attributes of variable speed systems need to be carefully tested to evaluate their performance from the utility point of view, i.e., a view of the machine from the generator terminals. With this purpose, the NASA experimental variable speed constant frequency (VSCF) system based upon a design by F. R. Schleif has been tested. The test configuration consists of a wound rotor induction generator and a line-commutated cycloconverter.

In order to determine the usefulness of these systems in utility applications, tests are required to resolve issues fundamental to electric utility systems. Legitimate questions exist regarding how variable speed generators will influence the performance of electric utility systems; therefore, from a utility perspective, tests have been performed on the VSCF system and an induction generator at an operating power level of 30kW on a system rated at 200kva and 0.8 power factor. Since the VSCF is an experimental type system, the results obtained here should be viewed from the perspective of research in progress. The results of the tests have been summarized in three categories: power quality, voltage/VAR management, and dynamic behavior.

The character of the power generated by the system has two predominant modes of oscillation: one that varies from 2p to 4p, and another mode that is associated with the slip frequency. In addition to this low frequency

behavior, harmonic currents of 60HZ appear to be large, especially at generator speeds near synchronous, while harmonic voltages appear to be typical, a direct result of the generator rotor controller design.

Although the generator rotor controller of the variable speed system behaves similarly to the excitation system of synchronous generators over a limited range in controlling the terminal voltage or the stator power factor, the VSCF system will always act as a net VAR sink. In order to use the VSCF system in a VAR dispatch mode, a supplementary capacitor is attached to the terminals of the generator to bias the level of reactive power supplied to the VSCF system. Such a configuration will permit the VSCF system to be an effective voltage/VAR management tool.

The ability of the built-in synchronizer to quickly adjust the phase angle and magnitude of the terminal voltage in combination with the governor like characteristics of the turbine controller, allow resynchronization of the WT generator following a major electrical disturbance without requiring a shutdown/startup sequence procedure. This will reduce the downtime of wind system; therefore, the stability and reliability of the power system may be actually enhanced as compared to convention induction or synchronous wind turbine systems.

## 1.0 INTRODUCTION

As efforts are accelerated to improve the overall capability and performance of wind-electric systems, increased attention on variable speed configurations has developed. A number of potentially viable configurations have emerged. Although the combination of generator types with converter options is large, it now seems that the double output induction and the line-commutated cycloconverter form the most attractive system with respect to present cost and performance.

Primary advantages of variable speed systems are:

- o Effective wind turbine (WT) system damping properties;
- o WTs can have droop speed characteristics by proper implementation of control;
- o WTs can have voltage/VAR control capabilities;
- o Potential for stand-alone WT operation; and
- o Motoring operation to assist in the start up sequence.

These characteristics of variable speed systems need to be carefully tested to evaluate their performance from both the WT designer and the utility points of view. With this purpose, a NASA experimental variable speed constant frequency (VSCF) system based upon a design by F. R. Schleif was developed for both laboratory and wind turbine testing [1]. The test configuration consists of a wound rotor induction generator and a line-commutated cycloconverter. This system has been developed for R&D applications, and as a result some of the design parameters are not representative of commercial systems.

In order to determine the usefulness of these systems in utility applications, tests are required to resolve issues fundamental to electric utility systems. Traditionally, the electric utility industry has dealt largely with synchronous generators. Legitimate questions exist regarding how variable speed generators will influence the performance of electric utility systems; therefore, tests from a utility perspective have been performed on the VSCF system and an induction generator at an operating power level of 30kW on a system rated at 200kva and 0.8 power factor.



## 2.0 WT SYSTEM DESCRIPTION

The MOD-0 is an experimental down-wind horizontal-axis type machine. Its propeller rotates at 20 rpm and has two 64.3-ft-long blades, each with 19.8 ft of controllable tip length. The blades are mounted on a hub that teeters to decrease hub bearing stress. Mechanical energy captured from the wind is transmitted to a wound rotor four-pole induction generator via a low speed shaft, a 45:1 ratio gearbox, and a high speed shaft coupled to the generator shaft through a set of V-belts with a 2:1 ratio. Connection of the electrical generator to the power system is made through a 480/7200 volt step-up transformer and a transmission line.

Access to the rotor windings of the wound rotor induction generator allows its operation in two modes: 1) as a regular induction machine with the possibility of connecting external resistors to the rotor to vary slip (per unit difference between stator and generator rotor speeds), and 2) as a variable speed constant frequency system in which stator frequency is kept constant regardless of generator speed by electronically controlling the frequency of the rotor voltage as in the VSCF system. The turbine control system controls the startup, synchronization and shutdown sequences, maintains the nacelle aligned into the wind, and controls normal operation of the WT. Synchronization and power generation are controlled differently according to the type of generator system being driven. Descriptions of turbine control and generator systems are given below. A pictorial representation of the MOD-0 system is shown in Exhibit 2.1.

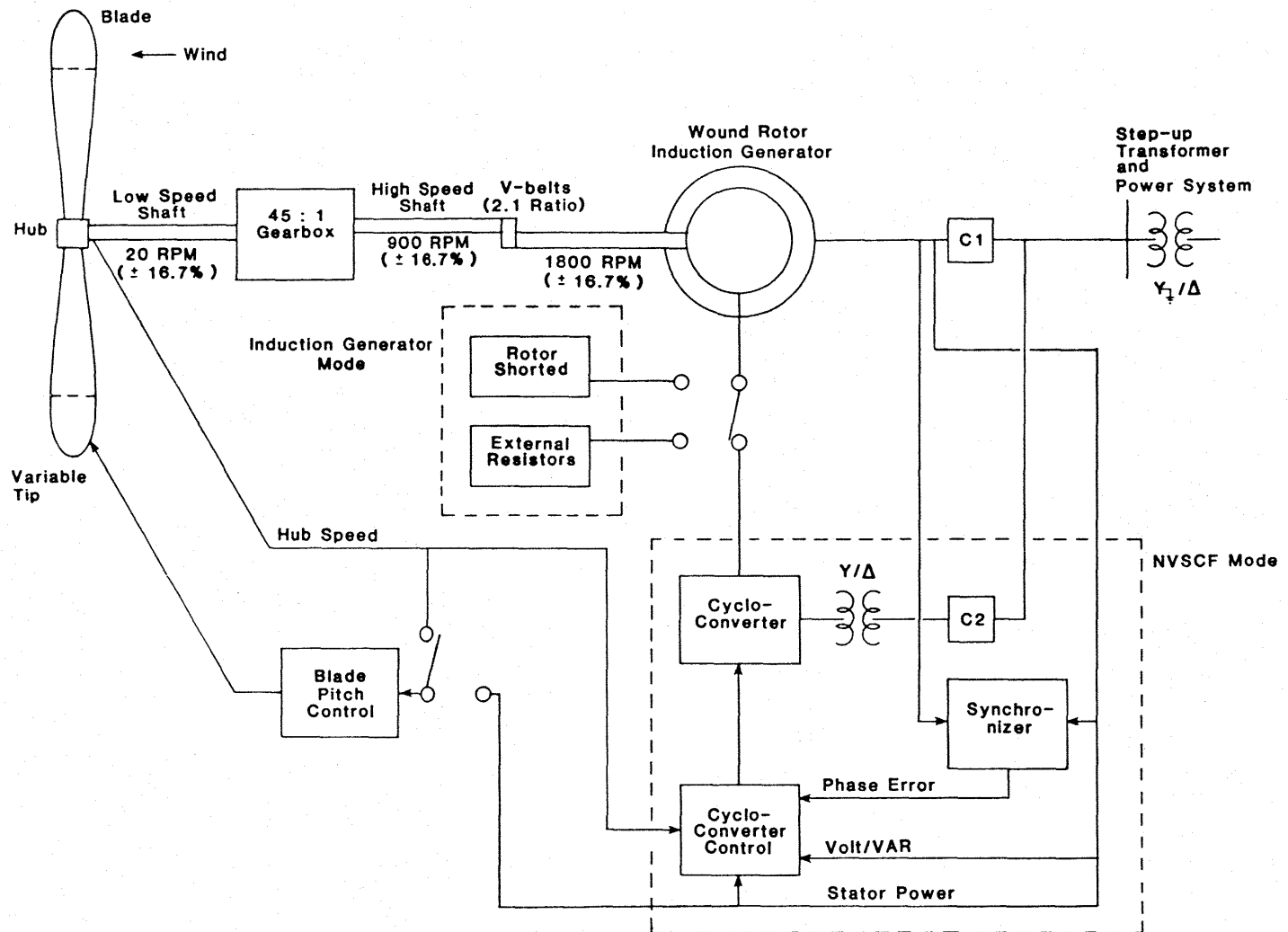


EXHIBIT 2.1 Pictorial Representation of MOD-0 Wind Turbine System

## 2.1. Turbine Control System

The wind turbine controller is based on a microprocessor system. One of the control functions is to keep the nacelle pointing into the wind to maximize energy capture (yaw control). Startup, synchronization, shutdown, and normal operation are also controlled by the microprocessor. Other functions include monitoring of wind and power output to initiate startup and shutdown sequences, and monitoring of different machine operating parameters to meet safety requirements. A detailed description of the control system can be found in reference [2].

During part of the startup procedure prior to synchronization the WT is placed under proportional plus integral speed control to vary blade pitch angle. Once the generator is connected to the network, stator power or hub speed error can be monitored by the blade pitch controller depending upon the type of generator system being driven, but the blade pitch control characteristics are still proportional plus integral (see Exhibit 2.2). For the induction generator mode, blade pitch control responds to stator power error above rated wind speed. If the wind speed is not enough to maintain rated output power, the blade pitch controller keeps the blade pitch angle fixed at zero degrees to capture maximum power. For the VSCF generator, blade pitch control is on hub speed error to maintain hub speed within limits over the entire power generating range. In addition, generator rotor controller regulates output power.

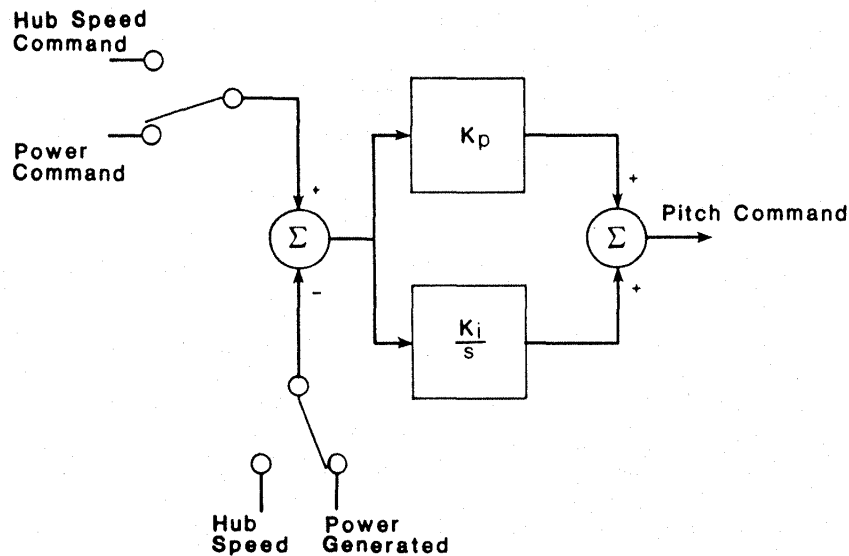


EXHIBIT 2.2 Blade Pitch Control Diagram

## 2.2 Generator Systems

The wound rotor induction generator is a 60Hz, 4 pole, 200 kva, 0.8 pf machine manufactured by Bogue Electric Manufacturing Company. Stator as well as rotor windings are wye-connected with access to the neutral, rated at 480 volts, and with a stator to rotor turns ratio of 1:2. The generator is designed to rotate at speeds in the 900 to 2700 rpm range. Since the machine

can be operated as a conventional induction generator or as the VSCF system, characteristics of both modes are reviewed in order to make the report as self-contained as possible. Additional information about both the induction generator and the VSCF system can be found elsewhere [1,3].

### 2.2.1. Induction Generator

To operate as a generator, the induction machine has to be driven at speeds higher than the speed of the stator field (the so-called synchronous speed); in other words, the induction generator has an inherent negative slip. Mechanical power supplied by the prime mover is transferred across the air gap to the stator, from which it is delivered to the load as electric power. The net output power is equal to the mechanical power input less rotational losses and rotor and stator copper losses.

Airgap torque-speed characteristics of the induction generator are similar to those of the induction motor. Torque is a function of slip and is proportional to the square of the terminal voltage. For a given generator, there is a maximum torque that can be delivered which is proportional to the square of the terminal voltage and is independent of speed and rotor resistance. However, the slip at which the maximum torque occurs is directly proportional to rotor resistance. This means that on the one hand, changing rotor resistance changes the slip at which a certain load can be supplied but not the maximum torque. On the other hand, varying terminal voltage changes the maximum torque but not the slip at which maximum torque is developed. As a result, the induction generator has two steady state stability limits. First, for a given terminal voltage, the machine can pull out of step when

slip exceeds its maximum value due to a sudden change of load. This phenomenon is similar to first-swing stability of a synchronous generator. Second, a sudden terminal voltage reduction can also make the machine step out of synchronism. This phenomenon is called voltage collapse stability [4].

Normally, induction alternators are designed with low rotor resistance to reduce rotor losses and to get efficiencies comparable to those of synchronous generators. In this case, the torque-speed characteristics become very steep and the range of generator rotor speed variations is reduced to the point that the machine will operate similar to a synchronous generator. However, the induction machine provides torsional damping not available with the synchronous generator. Additionally, the induction generator can not participate in voltage/VAR coordination or support system frequency.

#### 2.2.2 VSCF System

This system consists of a wound rotor induction generator and a variable frequency voltage source applied to the generator's rotor. By proper adjustments of the frequency of the rotor voltage, the generator shaft can revolve at speeds below, at, and above synchronous speed while the stator is delivering electric power at constant frequency.

Exhibit 2.3 shows a block diagram of the generator rotor controller used in the VSCF system. Three major elements can be identified: 1) a three-phase adjustable frequency signal generator, 2) a pulse generator, and 3) a 6-pulse cycloconverter. The adjustable frequency signal generator has a two-phase, 2 kHz sine wave master oscillator whose output frequency is changed between  $2\text{ kHz} + 10\text{ Hz}$  and  $2\text{ kHz} - 10\text{ Hz}$  by a voltage controlled oscillator [1].

Frequency of the signal generator depends upon hub speed and phase error (from

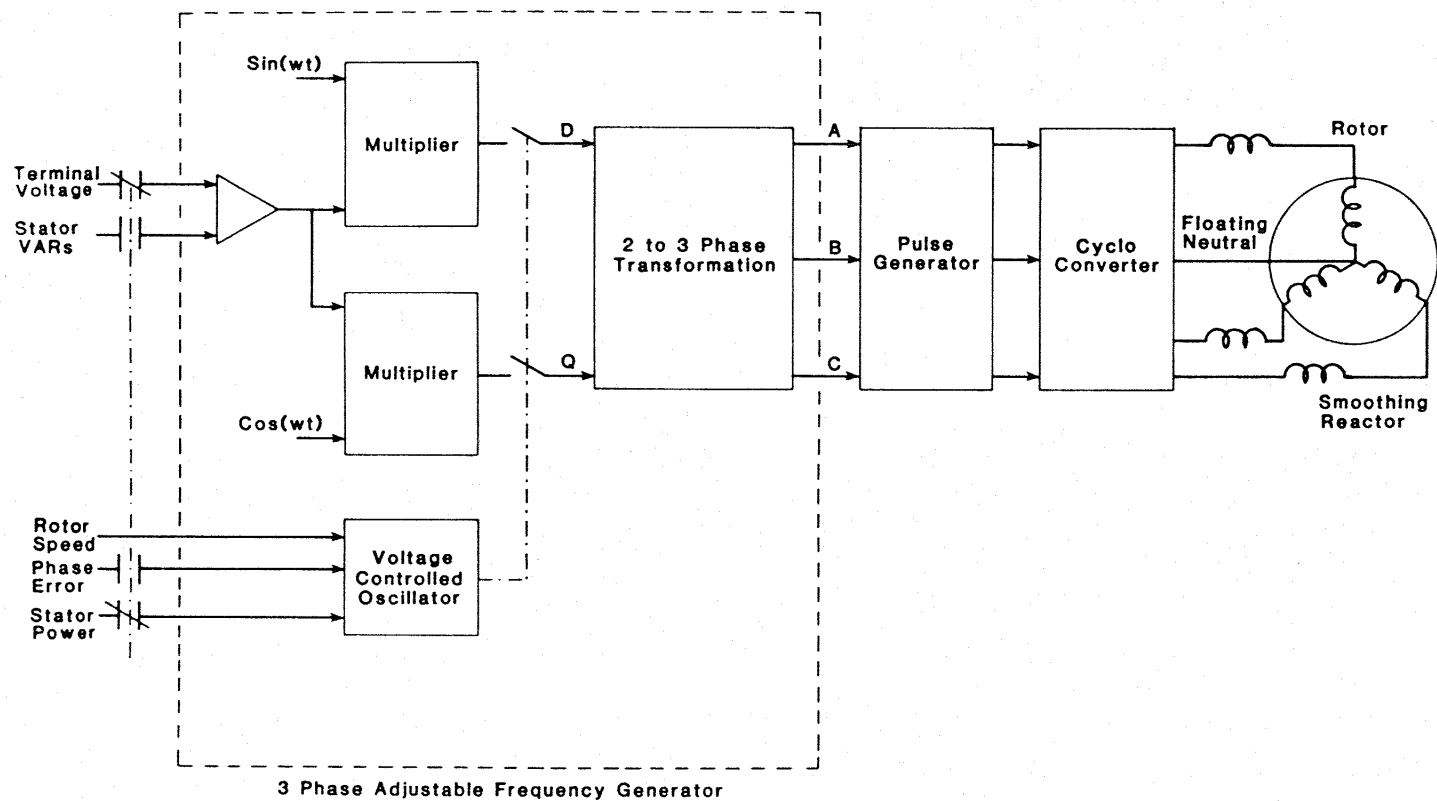


EXHIBIT 2.3 Block Diagram of Generator Rotor Controller for the VSCF System

a built-in synchronizer) prior to synchronization and upon hub speed and stator power after the system has been synchronized to the power grid. The magnitude of the frequency generator signal is controlled by stator voltage error before synchronization and either terminal voltage or stator reactive power error after connection to the power system. The two-phase variable frequency signal is then converted to a three-phase signal which is used to generate the pulses needed to control the switching operation of the cycloconverter's thyristors.

Each of the rotor windings is connected to a six-pulse cycloconverter as shown in Exhibit 2.4. The cycloconverter is isolated from the electrical grid by a 60 Hz, three phase, 480/330 volt transformer delta-ye connected. Basically the cycloconverter changes the 60Hz frequency of the reference (which in this case is the power grid) to a variable frequency signal between 0 and 10 Hz which is applied to the rotor windings. The ability of the cycloconverter to vary its output frequency and to conduct power in both directions allows the machine to revolve at different speeds between 1500 and 2100 rpm, converting the wound rotor induction generator in a true variable speed machine. In addition to this, rotor power which in a conventional induction machine is dissipated as heat can be recovered and injected into the power system. Power recovery is possible during supersynchronous operation. At subsynchronous speeds, the rotor absorbs power from the power system. Due to the capability of generating or absorbing rotor power, the wound rotor induction generator is also called a double-output induction generator or a doubly-fed induction generator.



Other characteristics of the VSCF system are:

- 1) Generation of power at constant 60 Hz frequency over a generator speed range of  $1800 \text{ rpm} \pm 16.7\%$ ;
- 2) Stator reactive power regulation capability;
- 3) Reduction of output power variations induced by wind speed changes;
- 4) Torsional damping;
- 5) Rapid synchronization (does not require external synchronizer).

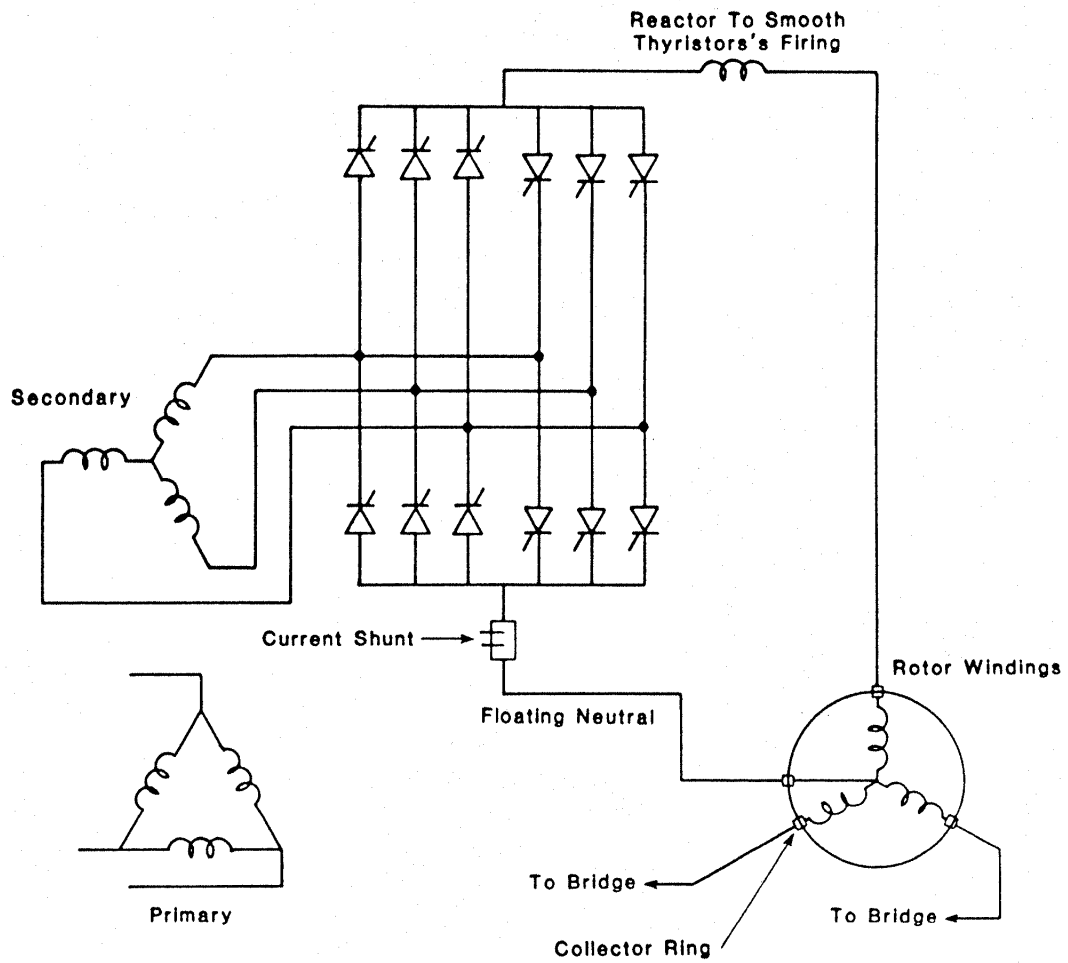


EXHIBIT 2.4 Line Diagram of 6-Pulse Cycloconverter

### 3.0 TEST OBJECTIVES

The overall objective of the tests is to characterize the interaction of the VSCF system with the electric power system. In order to evaluate the performance of this system, testing is classified under three major issues of utility concern:

- o How the quality of power is affected by the presence of the VSCF system;
- o How voltage/VAR management should be performed with the VSCF system; and
- o How the VSCF system reacts to network disturbances.

All tests described in the next three sections were performed on the VSCF generating system installed on the MOD-0 test turbine at Plum Brook Station, Sandusky, Ohio. A limited number of tests were conducted on the induction generator to serve as a basis for characterizing performance of the VSCF system.

Data was recorded on brush charts using instrumentation already available at the test site. In addition to the brush charts, spectral plots were obtained using a spectrum analyzer. The cycloconverter was operated in the six-pulse mode during the entire test period.

## 4.0 POWER QUALITY TESTS

These tests were intended to evaluate the quality of the power that the VSCF system delivers to the utility grid. The two major issues generally considered in the analysis of utilities' power quality are voltage/VAR requirements and waveform characteristics. At the Plum Brook test site, the WT is connected to a large power system via a strong tie; consequently, power variations induced by wind have little effect on the voltage profile at the point of interconnection and were neglected. Similarly, the effects of starting inrush currents on system voltage were not considered either. The main objective of the tests was to investigate how the voltage and current harmonics generated by the VSCF system may affect the power system at the intertie point. Reactive power requirements are considered in more detail in Section 5.

### 4.1 Test Procedure

Tests were performed on the VSCF system under two types of control. First, stator real and reactive power were manually set for different generator speeds spanning the system's range. Second, the WT automatically generated optimum power according to actual wind conditions.

During both control modes, spectral plots of voltage and current in the high voltage side (HVS) of the step-up transformer and voltage and current in the low voltage side (LVS) and stator power were recorded. These plots covered frequencies from 0.1 to 15Hz in the subharmonic range and from 4Hz to 600Hz in

the superharmonic range. At the same time that harmonic data was collected, stator voltage, wind speed, generator speed, stator voltage and current magnitude, generator real and reactive stator powers and cycloconverter real power were also recorded using chart recorders.

Tests were also run for the induction generator with its rotor terminals shorted to obtain nominal slip and with external resistors connected to the rotor terminals to obtain a 5% slip. Results of the tests are discussed below.

## 4.2 Test Results

As a consequence of time constraints in combination with some technical difficulties during the testing period, not all data could be recorded. Those tests for which most of the data was available are studied here. The analysis is divided into two categories: 1) harmonic current and voltages above 60Hz, and 2) low frequency (below 15Hz) stator power oscillations.

### 4.2.1 Harmonic Test Results

Exhibit 4.1.a shows the magnitude in percent of fundamental of the harmonics above 60Hz of the LVS and HVS voltage for the VSCF system running at 1500 rpm and generating 30kW at unity stator power factor. The cycloconverter is consuming approximately 126 kVARS. Exhibit 4.1.b shows harmonic voltages and currents in the LVS and the HVS for the VSCF machine running at 1800 rpm and for the same power level and power factor as at 1500 rpm. This time, the cycloconverter is drawing almost 120 kVARS from the system. In both cases,

EXHIBIT 4.1 HARMONICS FOR VSCF SYSTEM  
(% OF FUNDAMENTAL)

a. 1500 rpm, 30kW output, unity stator p.f.,  
cycloconverter consuming 126kVARs

Harmonic Order	HVS Voltage	LVS Voltage	HVS Current	LVS Current
2nd	n*	n	**	2.4
3rd	0.5	0.8		4.5
4th	n	0.2		2.2
5th	0.9	1.0		7.1
6th	n	0.5		4.5
7th	0.2	0.8		5.1
8th	n	0.1		n
9th	0.3	0.2		1.1
THD	1.1	1.6		11.3

\*negligible

\*\*data not available

b. 1800 rpm, 30kW output, unity stator p.f.,  
cycloconverter consuming 120kVARs

Harmonic Order	HVS Voltage	LVS Voltage	HVS Current	LVS Current
2nd	0.3	0.4	4.5	26.6
3rd	0.2	1.2	4.7	46.2
4th	0.2	0.3	2.2	23.7
5th	0.7	0.4	22.4	79.4
6th	0.1	0.1	1.6	8.2
7th	0.4	1.0	10.6	59.6
8th	n	0.1	0.9	6.8
9th	0.3	0.2	2.0	3.0
THD	1.0	1.7	25.8	115.7

the total harmonic distortion (THD) is calculated as the square root of the sum of the squares of each harmonic current/voltage expressed in percentage of fundamental.

$$THD = \sqrt{\sum_{i=2}^n (h_i)^2}$$

where

$h_i$  =  $i$ th harmonic current/voltage in percentage of fundamental

In general, the odd harmonics predominate over the even, especially the third, fifth, and seventh harmonic currents and voltages. Note that harmonic voltages and particularly the harmonic currents are attenuated by the step-up transformer (grounded wye-delta connected).

Harmonic currents and voltages produced by the VSCF generating system and the induction generator are presented in Exhibit 4.2. All quantities were measured in the LVS of the step-up transformer. The induction generator was running at 5% slip, generating 30kW and consuming 116 kVARs. The same two cases of the VSCF machine presented in Exhibit 4.1 are considered again (1800 and 1500 rpm). Although the THD in stator voltage is larger for the VSCF than for the induction generator, the difference is small and it should not present any potential problems for the utility (see Exhibit 4.2.a).

**EXHIBIT 4.2 HARMONIC VOLTAGES/CURRENTS  
IN THE LVS**

a. Harmonic Voltages (% of Fundamental)\*

Harmonic Order	Ind. Gen. on Line (5% slip, 30kW)	VSCF on Line (1800 rpm, 30kW, 1pf)	VSCF on Line (1500 rpm, 30kW, 1pf)
2nd	n	0.4	n
3rd	0.7	1.2	0.8
4th	n	0.3	0.2
5th	0.5	0.4	1.0
6th	n	0.1	0.5
7th	0.3	1.0	0.8
8th	n	0.1	0.1
9th	n	0.2	0.2
THD	0.9	1.7	1.6

b. Harmonic Currents (% of Fundamental)\*

Harmonic Order	Ind. Gen. on Line (5% slip, 30kW)	VSCF System on Line (1800 rpm, 30kW, 1pf)	VSCF System on Line (1500 rpm, 30kW, 1pf)
2nd	0.2	26.6	2.4
3rd	5.1	46.2	4.5
4th	0.2	23.7	2.2
5th	2.1	79.4	7.1
6th	n	8.2	4.5
7th	0.2	59.6	5.1
8th	n	6.8	n
9th	0.5	3.0	1.1
THD	5.5	115.7	11.3

\*Reactive Power Consumption:

Induction Generator - 116kVARs

VSCF's Cycloconverter (1800rpm) - 120kVARs

VSCF's Cycloconverter (1500rpm) - 126kVARs

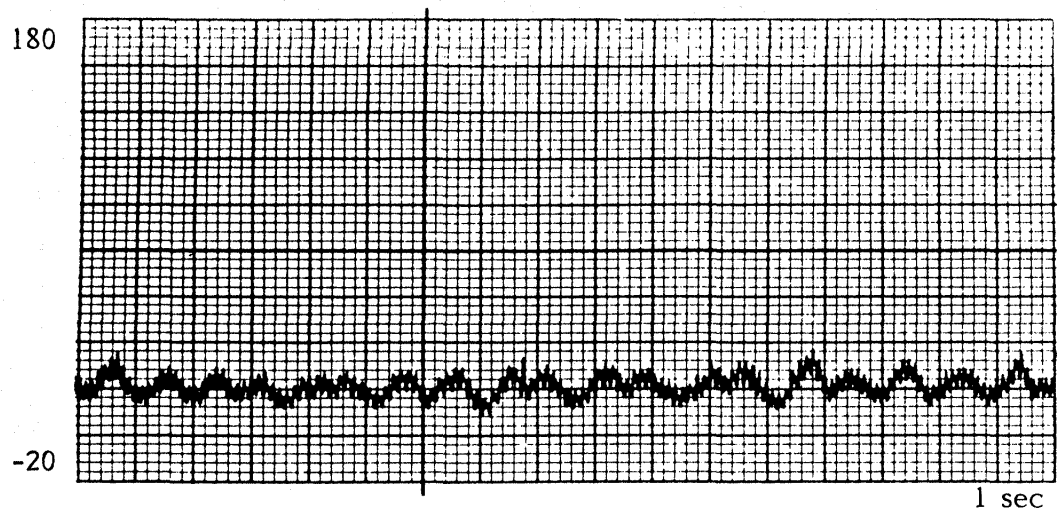


Harmonic currents generated by the VSCF system are larger than those produced by the induction generator, particularly at or near synchronous speed (see Exhibit 4.2.b). It has been found that for a single phase naturally commutated converter used in a photovoltaic application [5], the magnitude of harmonic currents remained practically constant for any load condition; thus, the THD decreased as load increased. This result might be expected for the VSCF system, but with the existing data it is difficult to determine how the THD will vary for different operating conditions. Again, all these results were recorded at low levels of power (30kW).

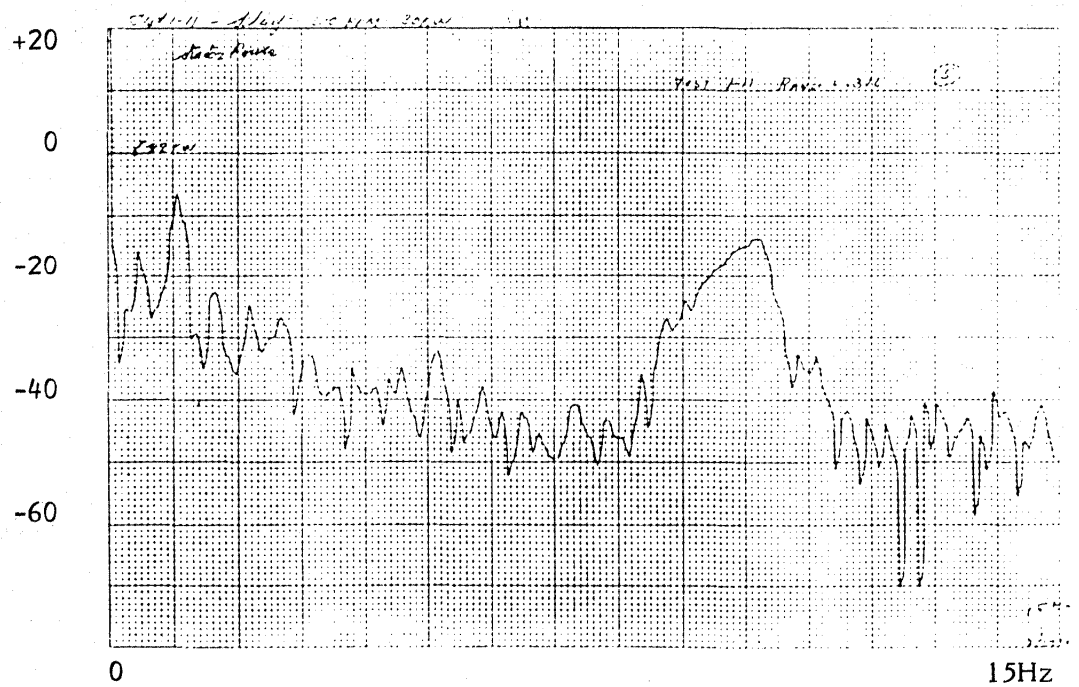
#### 4.2.2 Power Oscillation Test Results

Exhibit 4.3.a shows the stator power for the VSCF system running at 1500 rpm and generating 30kW at unity stator power factor. Two oscillations can be observed: one with a frequency of approximately 1.2Hz and the other with a frequency of about 10Hz. Since the slip is 3/18 pu, the rotor frequency is 10Hz ( $3/18 \times 60\text{Hz}$ ); thus, it is clear that the 10Hz oscillation is a result of slip frequency (see Exhibit 4.3.b). The origin of the 1.2Hz oscillation is not as evident, since it does not correspond to the two per revolution (2p) frequency which is 0.56Hz at 1500rpm. This observed frequency of oscillation is closer to 4p.

Those two power oscillations account for about 50% of the power set point (30kW for this test) for the 1.2Hz oscillation and 30% for the 10Hz oscillation. In a weak system, they may produce relatively large voltage oscillations which may be noticeable as flicker and that may reduce the performance of loads and power equipment such as voltage regulators and variable tap transformers. It is not clear if the percent magnitude of the



a. Stator Power (kW) vs. Time (sec)



b. Spectral Plot of Power in Db vs. Frequency in Hz

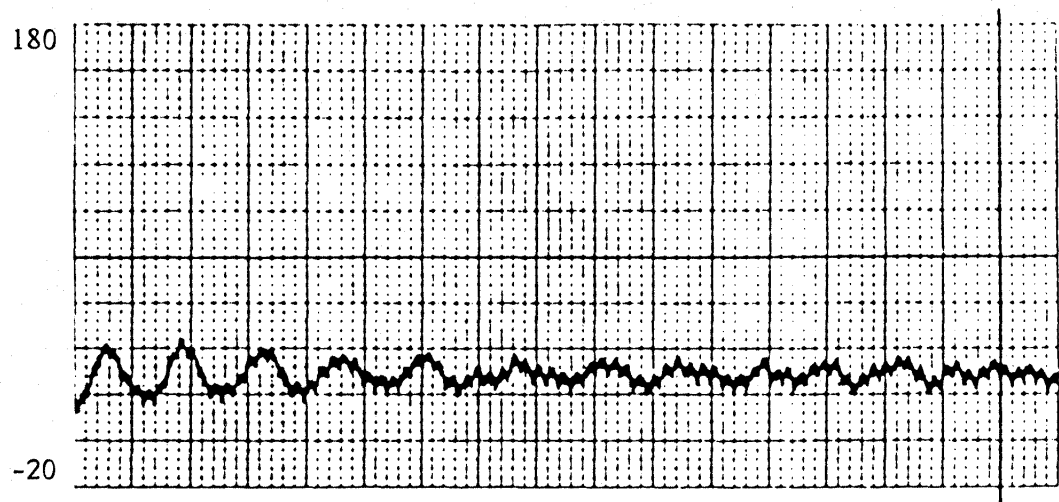
EXHIBIT 4.3 Low Frequency Oscillations in Stator Power of VSCF System (1500rpm, 30kW, 1pf)

oscillations will remain approximately the same for different output power set points or if they will decrease as generation increases. Of course, the generator rotor frequency oscillations will decrease as the rotor speed approaches synchronous speed.

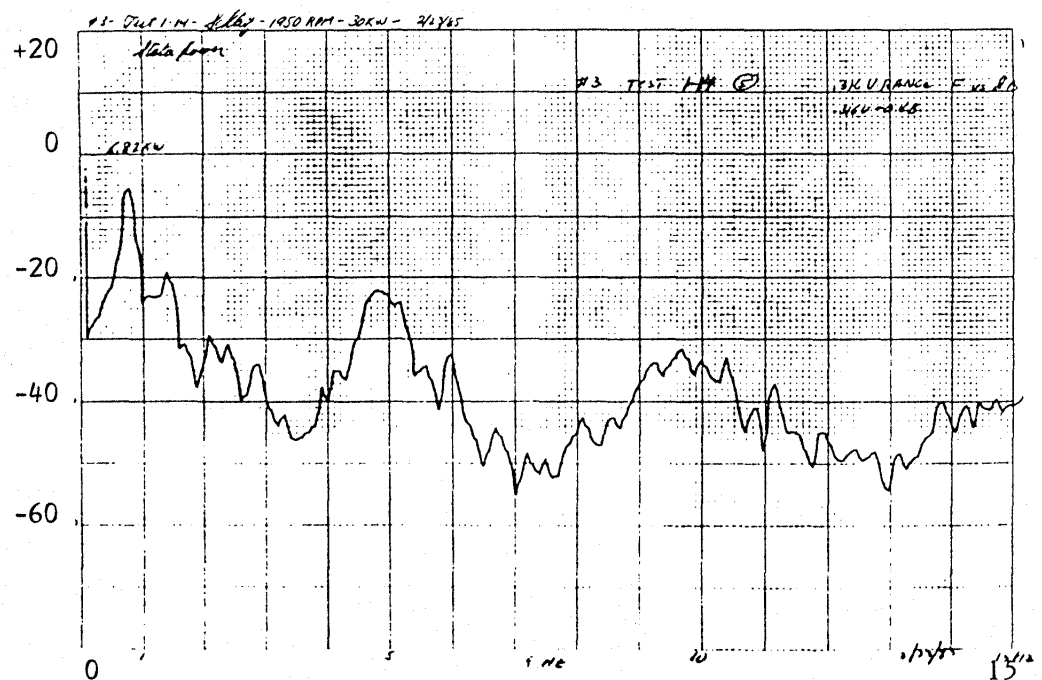
A similar analysis has been done on the VSCF system rotating at 1950 rpm (see Exhibit 4.4). At this speed, power oscillations occur at 5Hz and 0.8Hz. The former is thought to be associated with slip frequency ( $1/12 \times 60\text{Hz}$ ) while the latter appears at approximately  $2p$  (0.72Hz).

At 2100 rpm, the cycloconverter power, stator current and stator power present oscillations with a frequency of 0.8Hz, which is roughly the  $2p$  frequency of the turbine. These oscillations may be large enough to eventually pull the generator out of step, as happened when the reactive power level was 50kVAR lagging (unfortunately, no charts were available). Oscillations at slip frequencies also become larger near maximum or minimum speed.

From these test results, it is observed that two predominant modes of stator power oscillation exist. One mode is associated with the slip frequency. A second one varies between  $2p$  and  $4p$  and its origin is not obvious. At least two candidate explanations exist: 1) an oscillatory mode introduced by the interaction of the generator rotor controller and the  $2p$  input, and 2) stimulation of the first torsional mode by the generator rotor controller.



a. Stator Power (kW) vs. Time (sec)



b. Spectral Plot of Power in dB vs. Frequency in Hz

EXHIBIT 4.4 Low Frequency Oscillations in Stator Power of VSCF System (1950rpm, 30kW, 1pf)

## 5.0 VOLTAGE/VAR MANAGEMENT

An important issue in planning and operation of power systems is the management of reactive power to provide efficient operation and shape voltage profile. Traditionally, generating plants have synchronous generators that can participate in the dispatch and control of system reactive power. It is the purpose of the tests specified in this section to assess the capability of the VSCF generating system to support reactive power coordination within its entire operating range.

### 5.1 Test Procedure

Three sets of tests were performed with the VSCF system under manual control. First, the WT generator was run at 1500, 1800 and 2100 rpm for three different stator reactive power levels: 50kVAR leading (producing VARs), unity power factor, and 50kVAR lagging (consuming VARs). In all cases, the power demand was 30kW. Second, for the same generator speeds and stator reactive power, the power demand was stepped from 0kW to 20kW. Finally, the generator terminal voltage was stepped down and up 5% for three rotor speeds and output power of 30kW at unity power factor. A voltage regulator located in the HVS of the 480/7200V transformer was used to initiate the voltage changes. Since the regulator taps cannot be changed instantaneously, the line voltage was actually ramped at a 2.5V/s ratio. This experiment was repeated with the inclusion of a 0.55pu reactor in series with the stator windings to weaken the intertie.

## 5.2 Typical Voltage/VAR Characteristics

The VSCF system provides the wound rotor induction generator with a means to control the stator power factor as shown in Exhibits 5.1, 5.2 and 5.3. Variables shown in those exhibits are generator speed (rpm), line-to-neutral stator voltage (volts), wind speed (mph), blade pitch angle (degrees), stator current (amps), stator reactive power (kVAR), cycloconverter power (kW), and stator power (kW) for a generator output power of 30kW and for VAR demands of 50kVAR leading (Exhibit 5.1), zero kVAR (Exhibit 5.2) and 50kVAR lagging (Exhibit 5.3). Additional variables have been shown to illustrate the conditions under which the voltage and VAR tests were conducted.

There are some results common to all cases mentioned above. For instance, although theoretically active power can be recovered from the rotor circuit for generator speeds above synchronous, the cycloconverter was consuming power below, at, and above synchronous speed regardless of stator power factor. Cycloconverter power consumption decreased as speed increased, but it was always flowing from the power system into the generator rotor. This may be the result of excessive capacity, that is, excessive no-load losses in the cycloconverter transformers.

Although terminal voltage does not seem to be very constant, no flicker problems at the control house were reported. The spikes present in the voltage appear to be the result of connection of the instrumentation rather than a generating system problem.

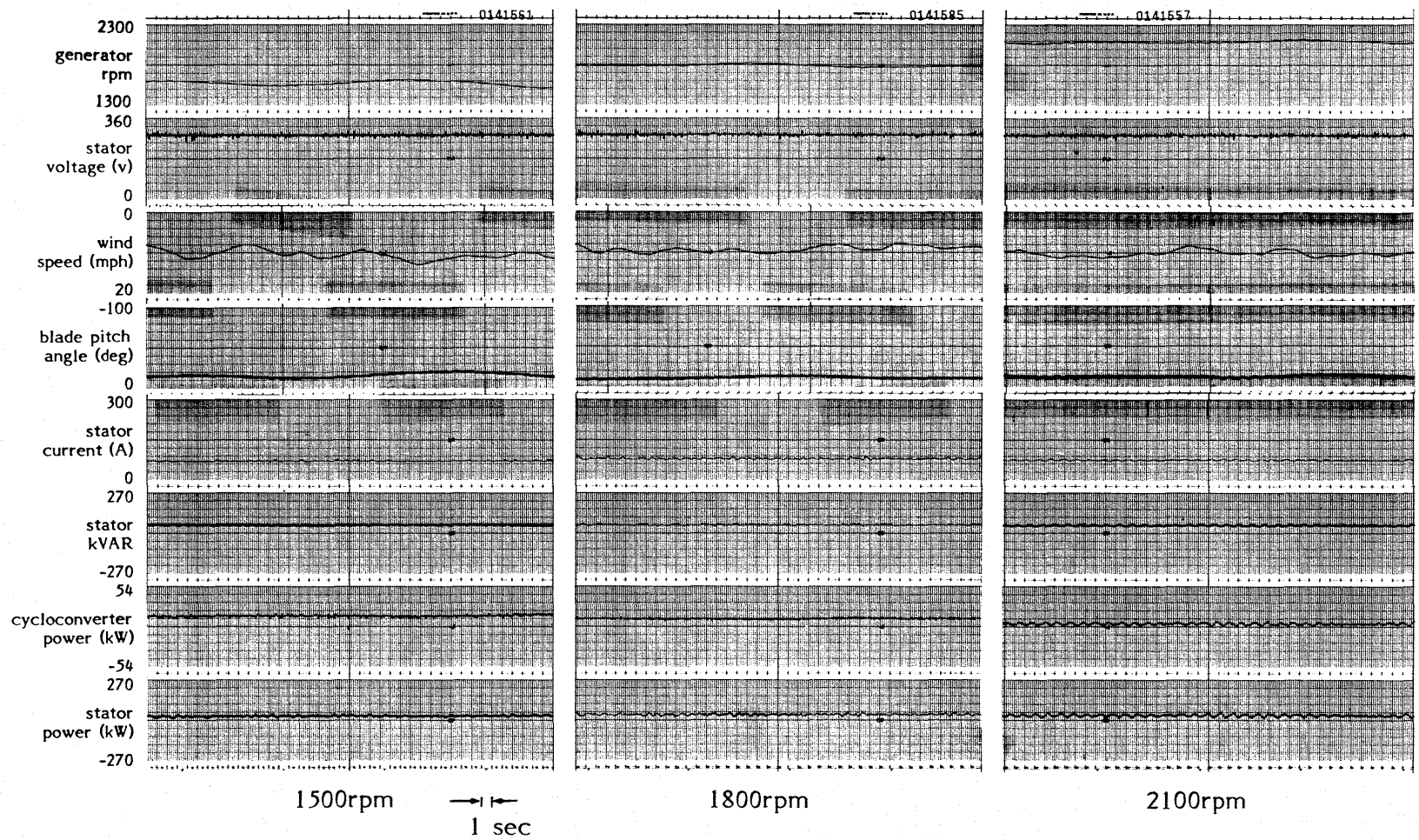


EXHIBIT 5.1 VSCF System Generating 30kW and 50kVAR Leading

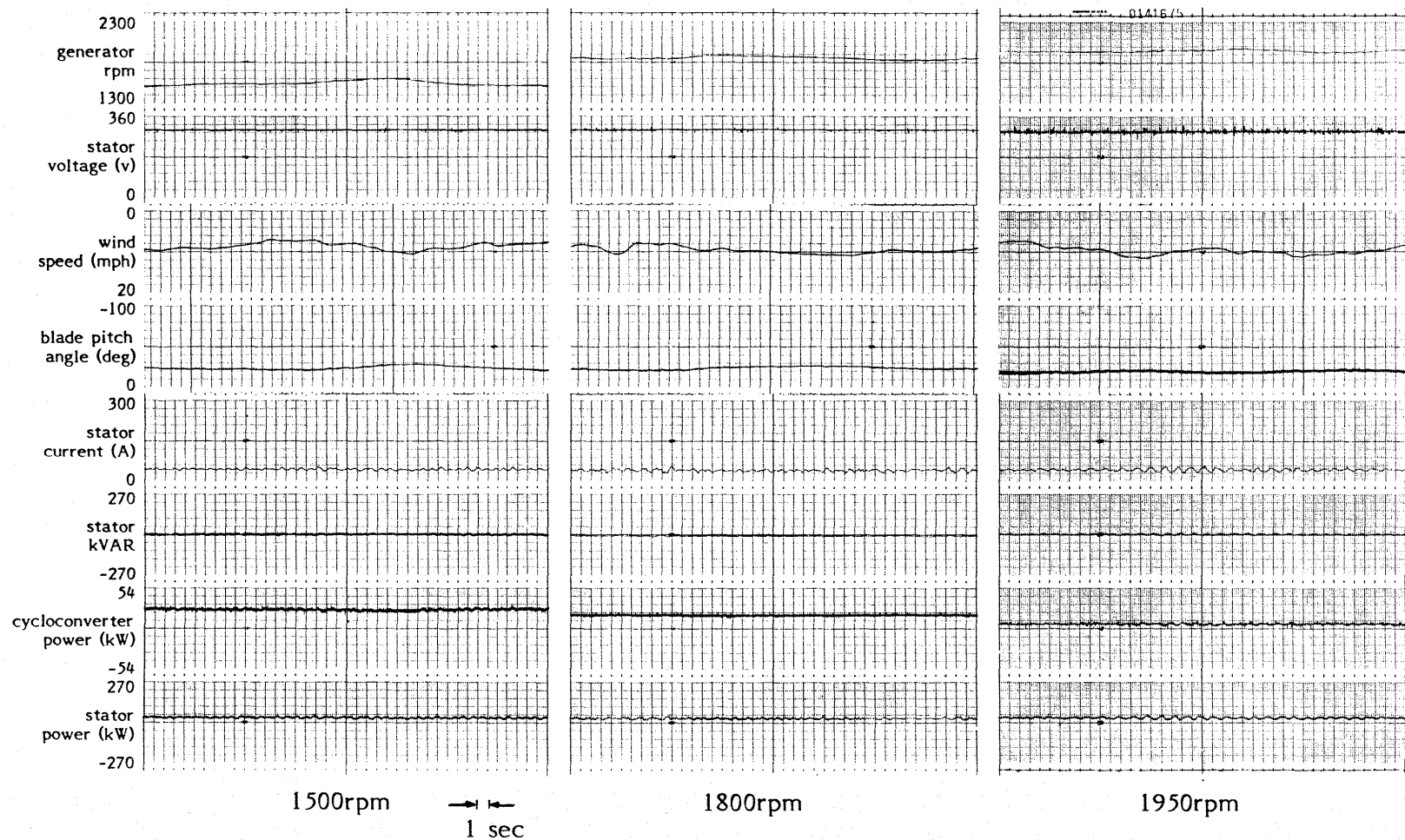


EXHIBIT 5.2 VSCF System Generating 30kW at Unity Power Factor



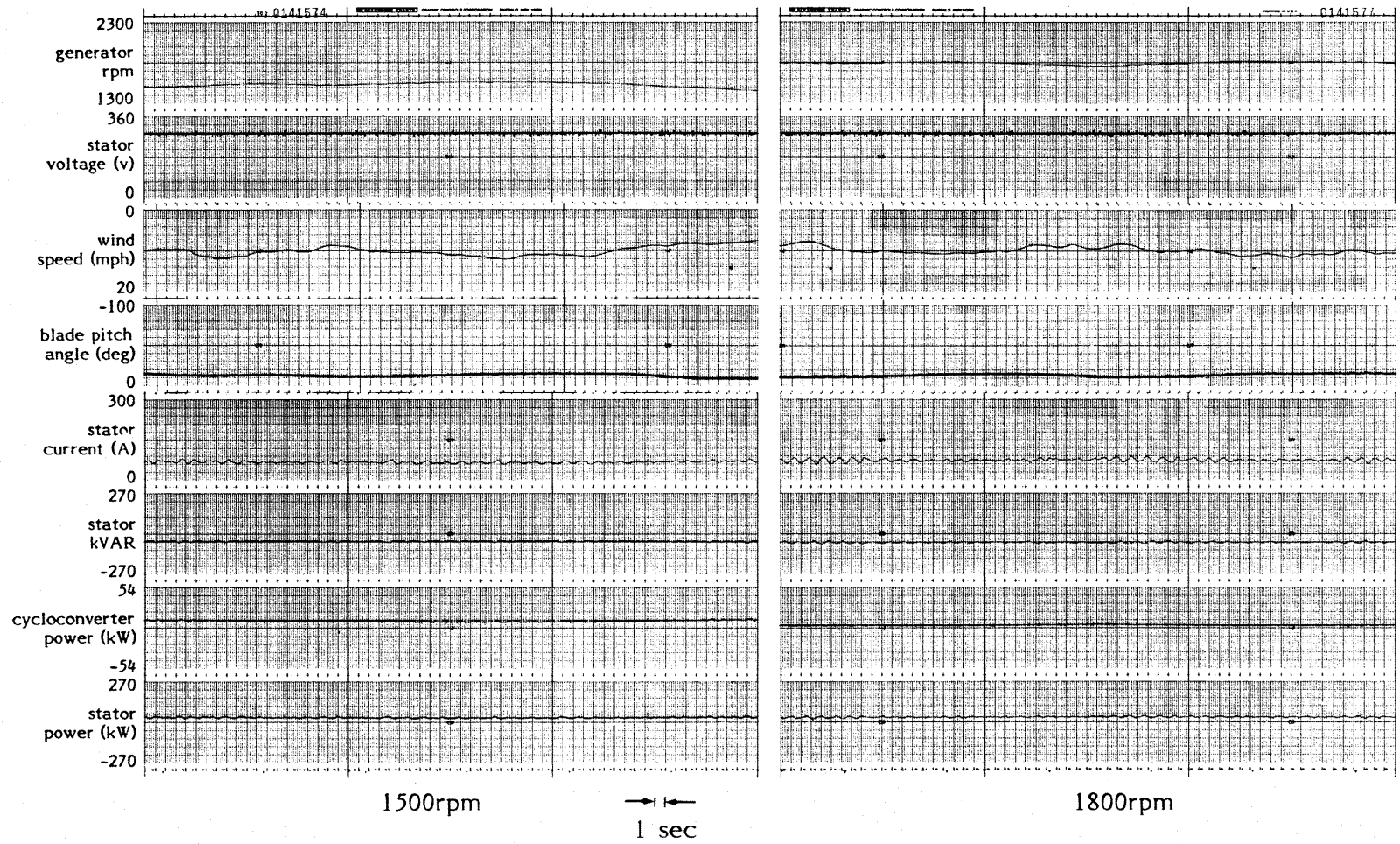


EXHIBIT 5.3 VSCF System Generating 30kW and 50kVAR Lagging

From a utility perspective, the VSCF system appears as a variable reactive load. A property of the VSCF system is its ability to either produce or consume VARs in the stator circuit; however, the generator rotor controller circuit always consumes more reactive power than is produced in the stator. Therefore, the VSCF is always a net VAR sink.

Since the VSCF system has a controllable VAR capability in the stator circuit, the system can be used in VAR management applications. When the VSCF is supplemented with an external capacitor, the combination can provide a net reactive power capability, either producing or consuming VARs. The capacitor serves as a bias level for the reactive power supply, and its magnitude will be determined by specific applications.

### 5.3 Power Step Tests Under Constant Reactive Power Demand

Exhibit 5.4 shows the response of the generator to a step change in power demand of 20kW. Initially the WT is operating as a synchronous reactor generating 0kW and 50kVAR leading (these power levels are measured at the generator terminals). The power setting is stepped from 0 to 20kW for generator speeds of 1500, 1800 and 2100 rpm. At 1500 and 1800 rpm, generator response is quick and smooth. The new power level is reached in about 0.3 second with virtually no overshoot. Although at 2100 rpm the new level is reached in about 0.2 second, the power overshoots, producing an oscillation of approximately 0.8Hz which corresponds to the 2p frequency. These oscillations disappear in almost two seconds.

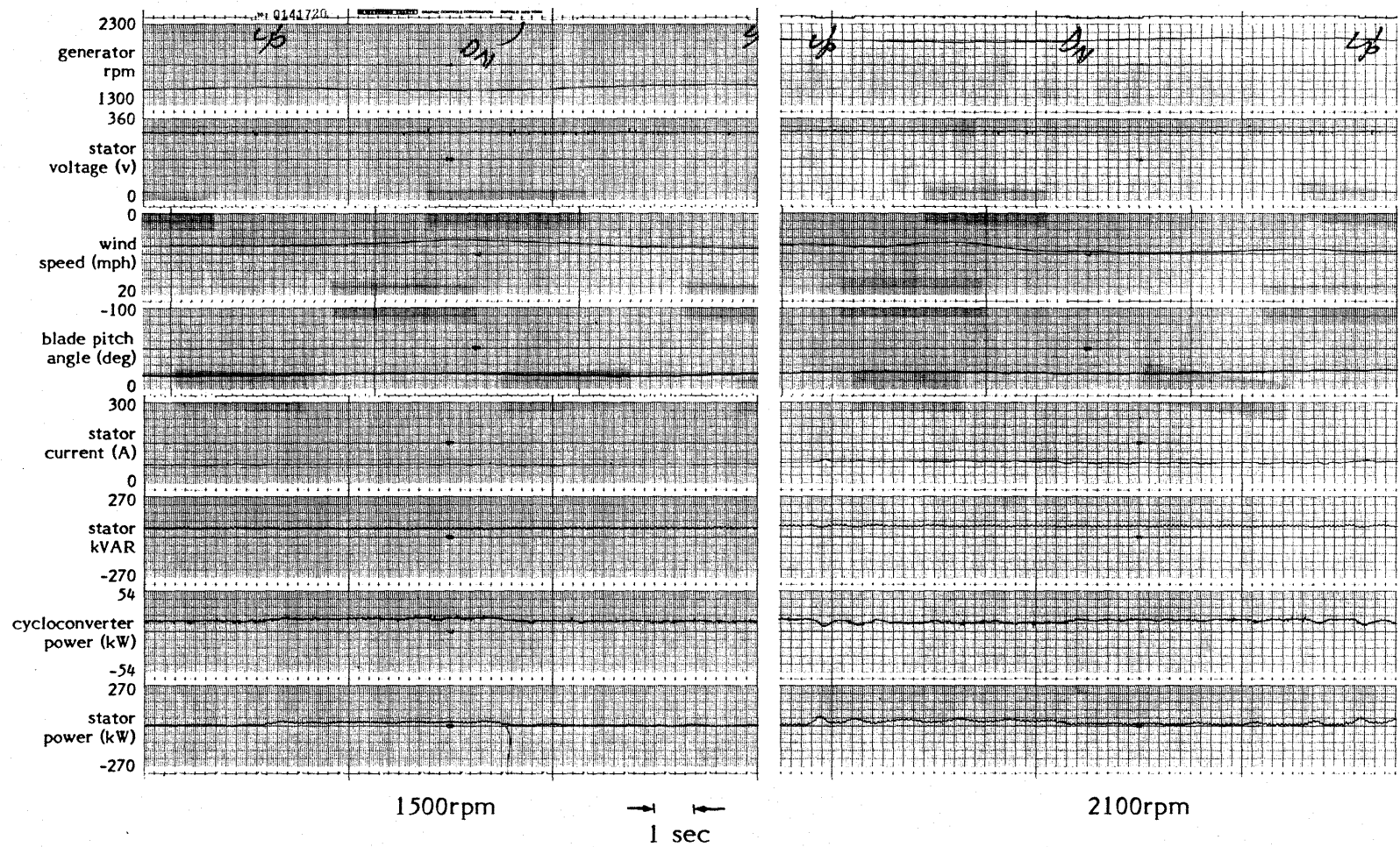


EXHIBIT 5.4 Step Changes in Power Demand at 50kVAR Leading

Changes in power demand are reflected as changes in kinetic energy of the drive train, i.e., generator speed decreases to accommodate the increase in generator load. Since the generator rotor power changes with slip, speed variations are also reflected as changes in cycloconverter output power level. Note that stator reactive power is not affected by changes in power demand, i.e., it remains practically constant within the operating speed limits. Similar results can be observed in Exhibits 5.5 and 5.6 which show the responses to the same disturbance but for unity stator power factor and 50kVAR lagging, respectively.

#### 5.4 Voltage-Step Tests Under Constant Power and Power Factor

Voltage variations at the interconnection point do not alter the stator reactive power generated by the VSCF system as it is illustrated in Exhibit 5.7. Generator terminal voltage follows the utility voltage profile. Decreases (increases) in power system voltage produce decreases (increases) in generator terminal voltage. The same results are observed when the generating system is connected to the grid via a weaker tie (see Exhibit 5.8).

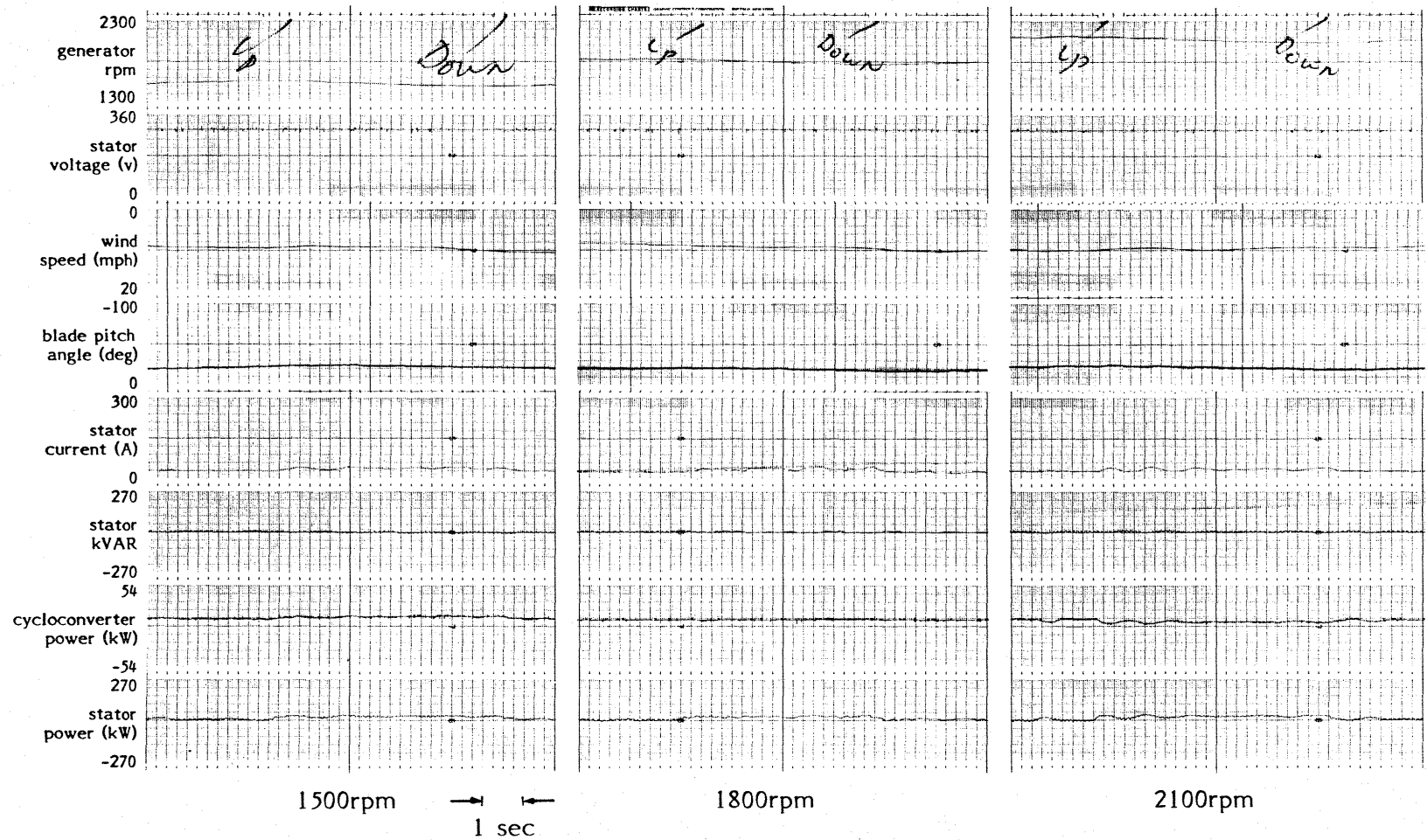


EXHIBIT 5.5 Step Changes in Power Demand at Unity Power Factor

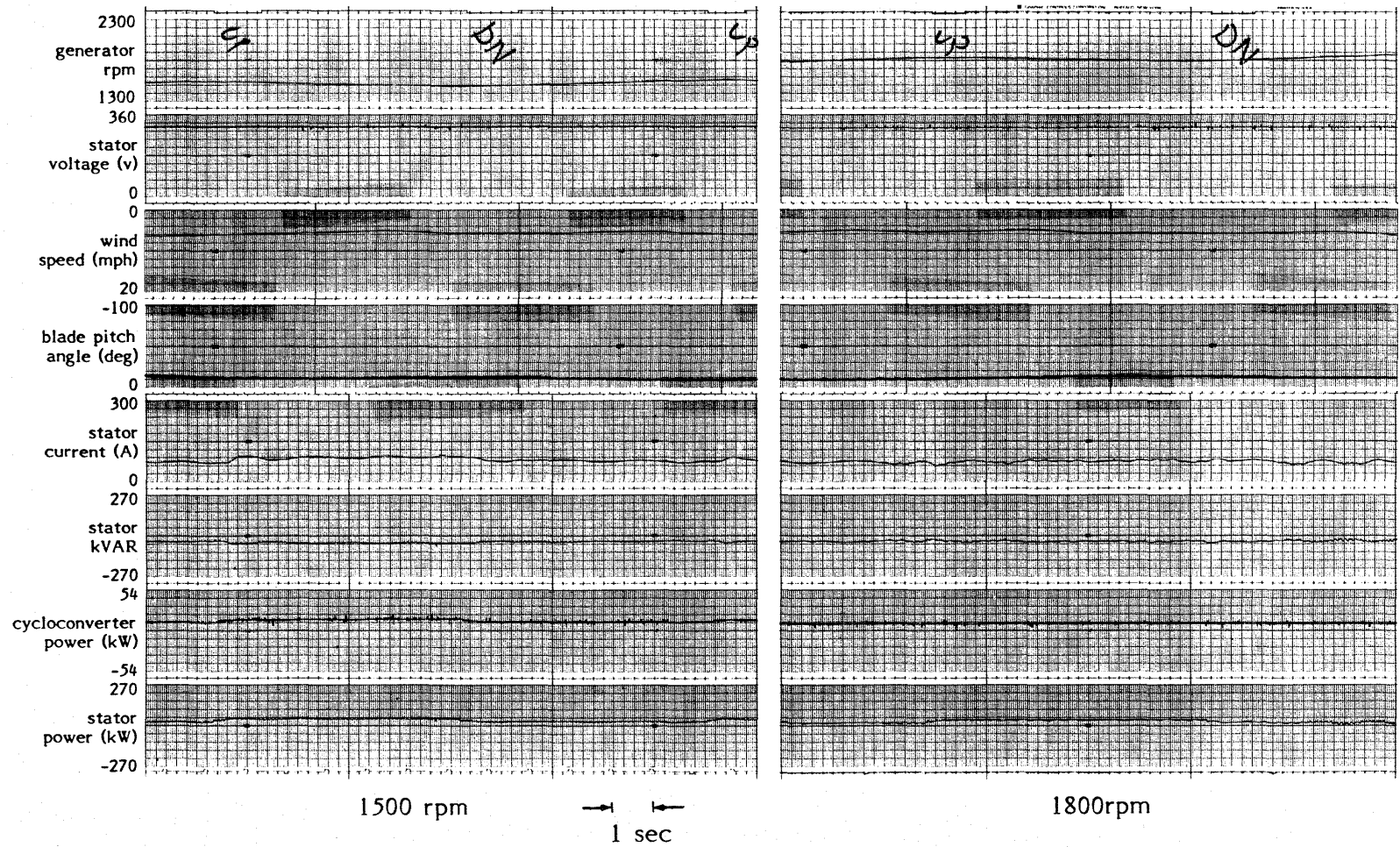


EXHIBIT 5.6 Step Changes in Power Command at 50kVAR Lagging



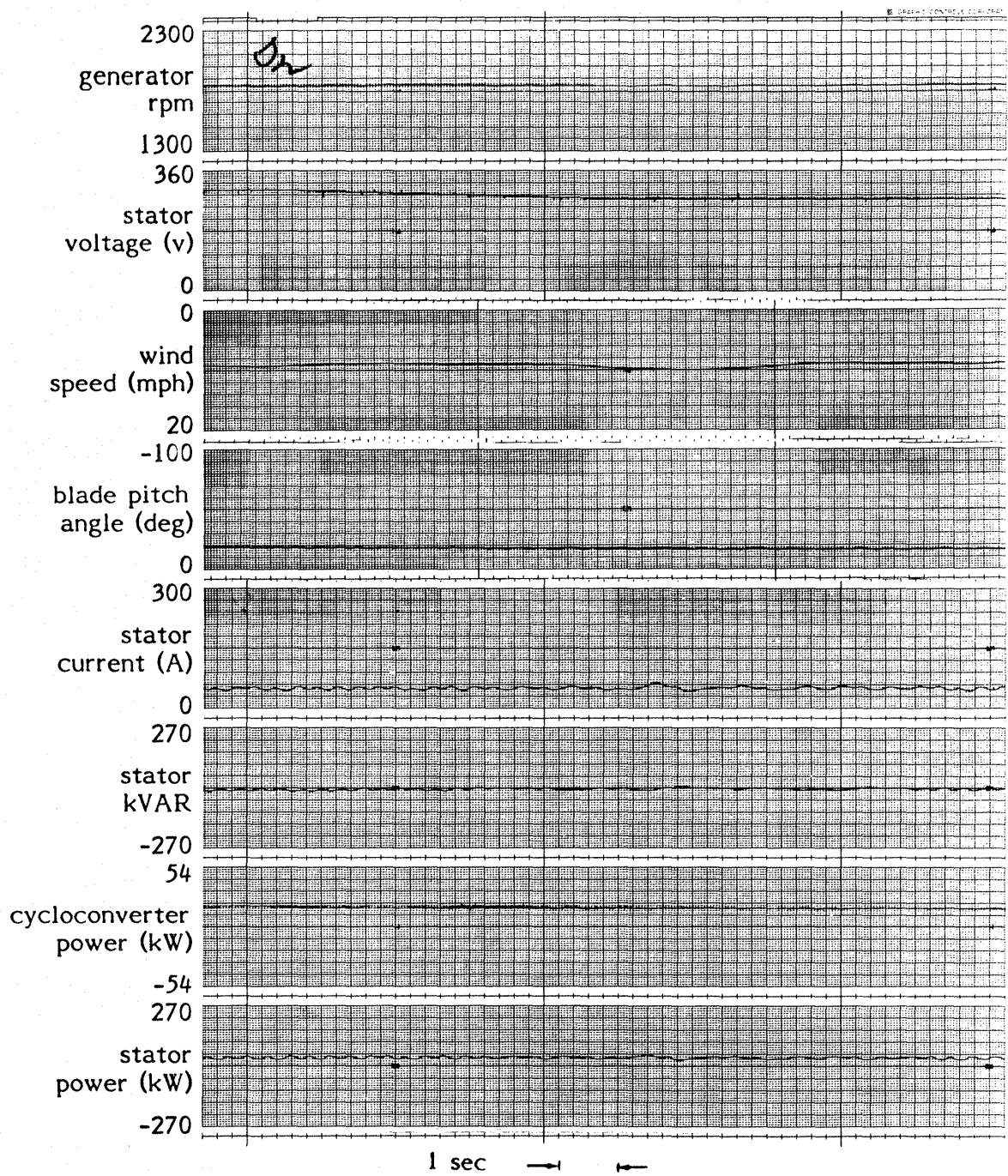


EXHIBIT 5.7 10% Voltage Reduction (stronger tie),  
VSCF System at 1800rpm, 30kW, 1pf

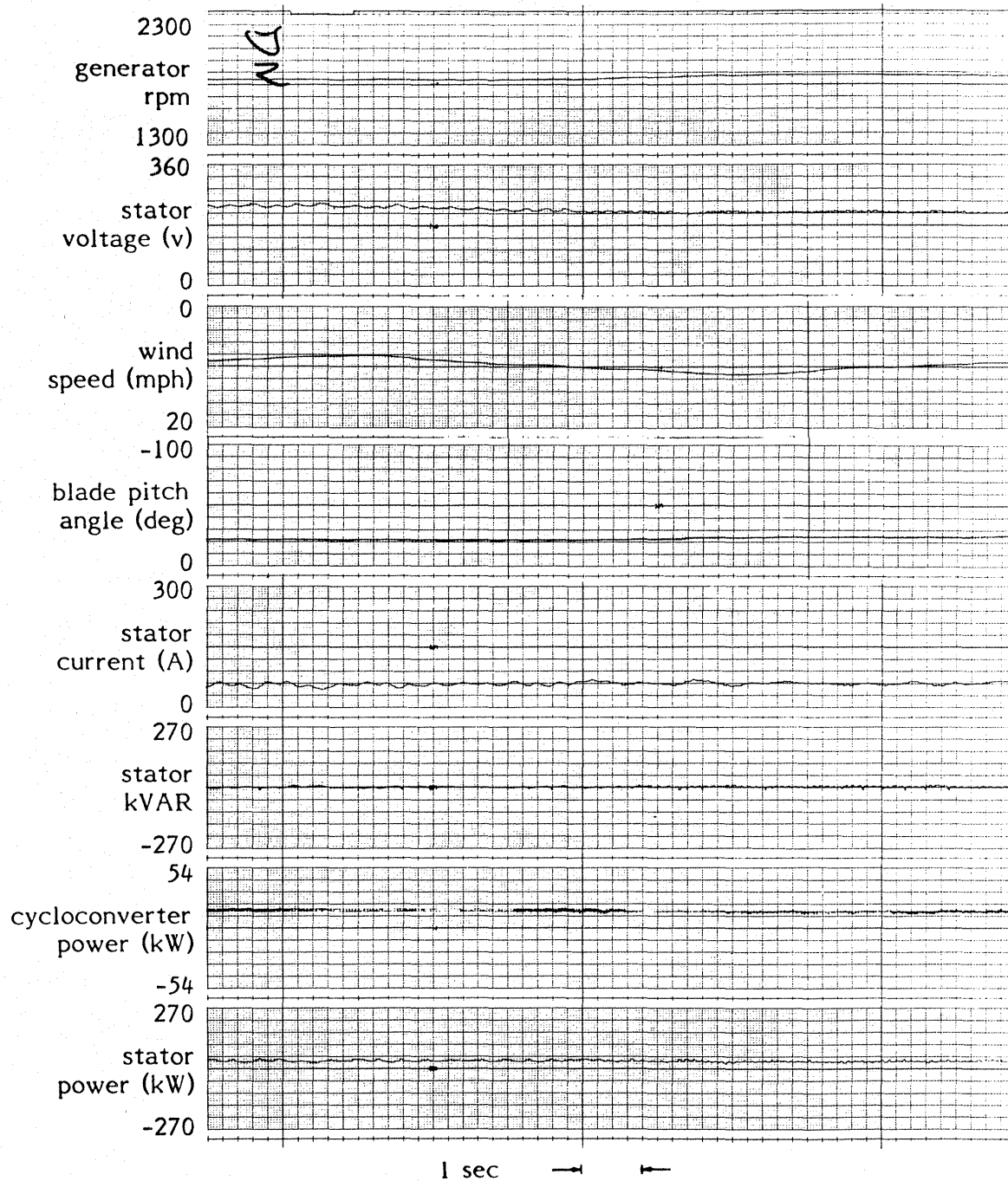


EXHIBIT 5.8 10% Voltage Reduction (weaker tie),  
VSCF System at 1800rpm, 30kW, 1pf



## 6.0 TRANSIENT STABILITY TESTS

Historically, electric utilities have routinely used automatic reclosure following system faults in order to quickly return the power transmission system to its normal configuration. Primary reasons for using automatic reclosure are to avoid system operating problems and to reduce expenditure of manpower. Since transmission of power is interrupted only momentarily, the reclosure operation contributes to a high reliability of service, enhances system stability, and minimizes the ramping of generating units assigned to automatic generation control (AGC). A set of tests were developed to study the applicability of reclosure with the VSCF system following loss of its output. Description of these tests and the results are presented below.

### 6.1 Test Procedure

With the machine generating 30kW, load rejection was simulated by opening the generator circuit breaker (C1 in Exhibit 2.1, page 6). Reclosure was performed 0.2 second and 1.0 second after loss of output. A third case was run in which the normal resynchronization procedure was followed. In this last case, the breaker is not closed until the frequency and phase of the generator's terminal voltage matches the frequency and phase of the grid's voltage. If the phase angle is kept within five degrees or less during one to five (or more) seconds, the breaker is directed to reclose.

Simulation of generator loss of output power did not include opening of the cycloconverter breaker (C2 in Figure 2.1) because the cycloconverter must be connected to the network in order to get power and the reference frequency that is necessary for its operation.

## 6.2 Test Results

The current WT reclosure procedure recommended by manufacturers is to shut down the machine following a large electrical disturbance, such as a short circuit near or at the generator terminals or loss of generator output, to avoid any risk of drive train damage. In other words, the major concern has been on the possibility of damage to the WT and not on the possible impact on the power system. The latter issue becomes particularly important as the penetration of wind generation increases. Utilities maintain excess transmission and generation capacity (system reserves) so that no credible contingency, be it a temporary electrical fault or the sustained loss of a major generating unit, is likely to result in unstable operation or cause the AGC system to violate existing operating guidelines. The amount of reserve maintained depends on a reliability analysis which considers the effects of various disturbances on the system and the probability of occurrence of those disturbances.

Alternative reclosure schemes considering both the possibility of exceeding stress limits in the WT's drive train and the potential operational problems (stability and AGC) of the interconnected system require modifications of the control philosophy of the constant speed constant frequency generating system. These systems have a blade pitch controller designed to feather the

blades to maintain constant output power and hub speed during wind conditions above rated and to keep the blade fixed in the position of maximum power capture during winds above cut-in and below rated such that power changes as the wind changes.

Variable speed systems control real power, reactive power or terminal voltage with the excitation system, while the blade pitch controller is always active monitoring hub speed. Since the frequency and phase of the stator voltage can be quickly adjusted independently of hub speed, reclosure can be attempted within tens of seconds after the initiation of a disturbance without going through the entire shutdown/startup/synchronization procedure.

Exhibits 6.1 and 6.2 show the response of the VSCF system to uncontrolled reclosure after 0.2 and 1 second from the time that the breaker was opened. In both cases, the electrical transients decay in about 0.8 second and all other activity stimulated by the switching vanishes in 1.5 seconds. The remaining oscillation at the slip frequency is induced by the generator rotor controller as it was discussed in Section 4 (Power Quality). Since the severity of the transients depend upon the prefault conditions, and during the tests the output power level was about 30kW (which is almost 20% of rated power of the generator), it is difficult to predict if stability could be maintained for the worst case, which is loss of rated load. However, even following normal resynchronization, the VSCF system will enhance the reliability of the power system over a constant speed constant frequency system.

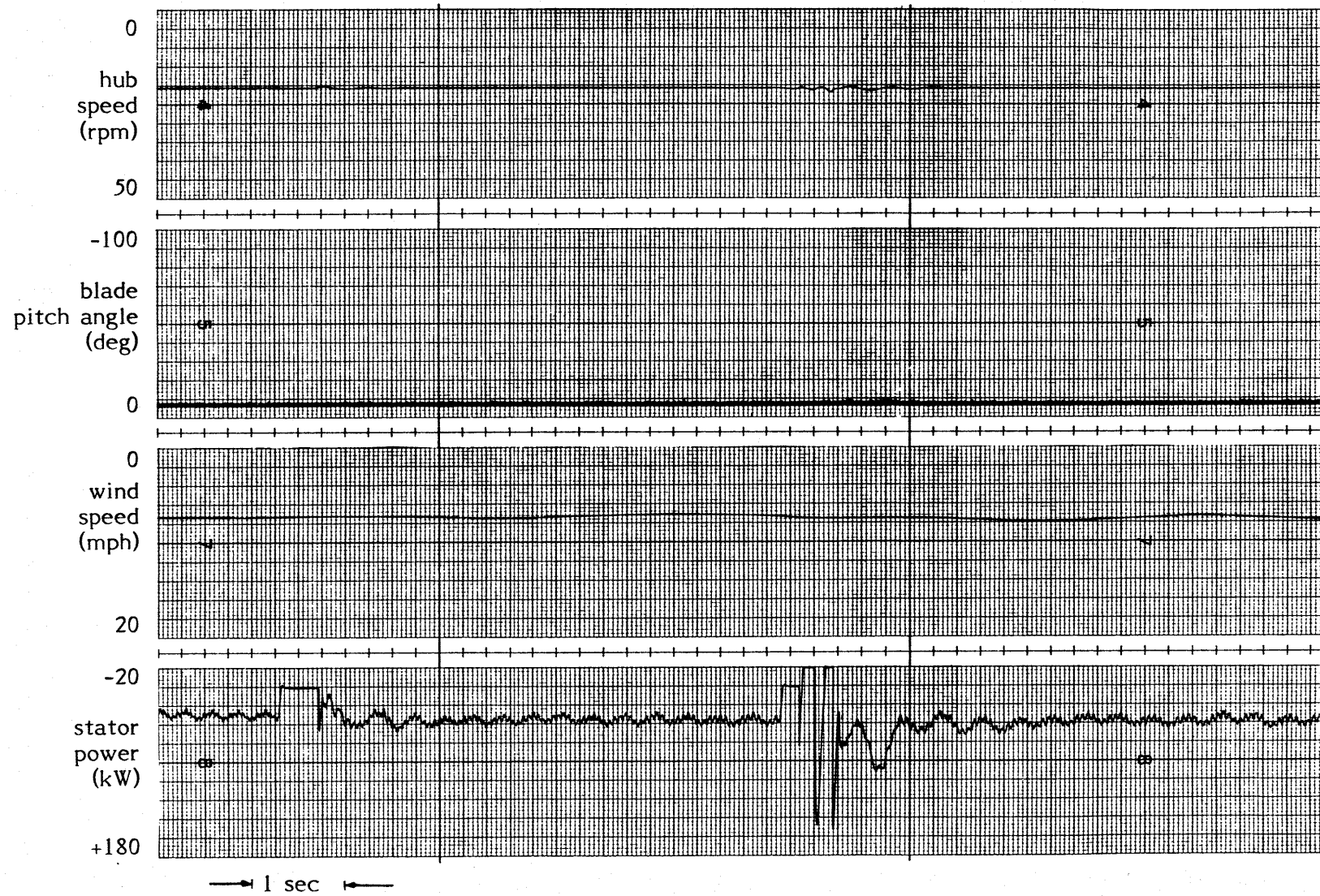


EXHIBIT 6.1 Loss of Output for 0.2 sec with VSCF System

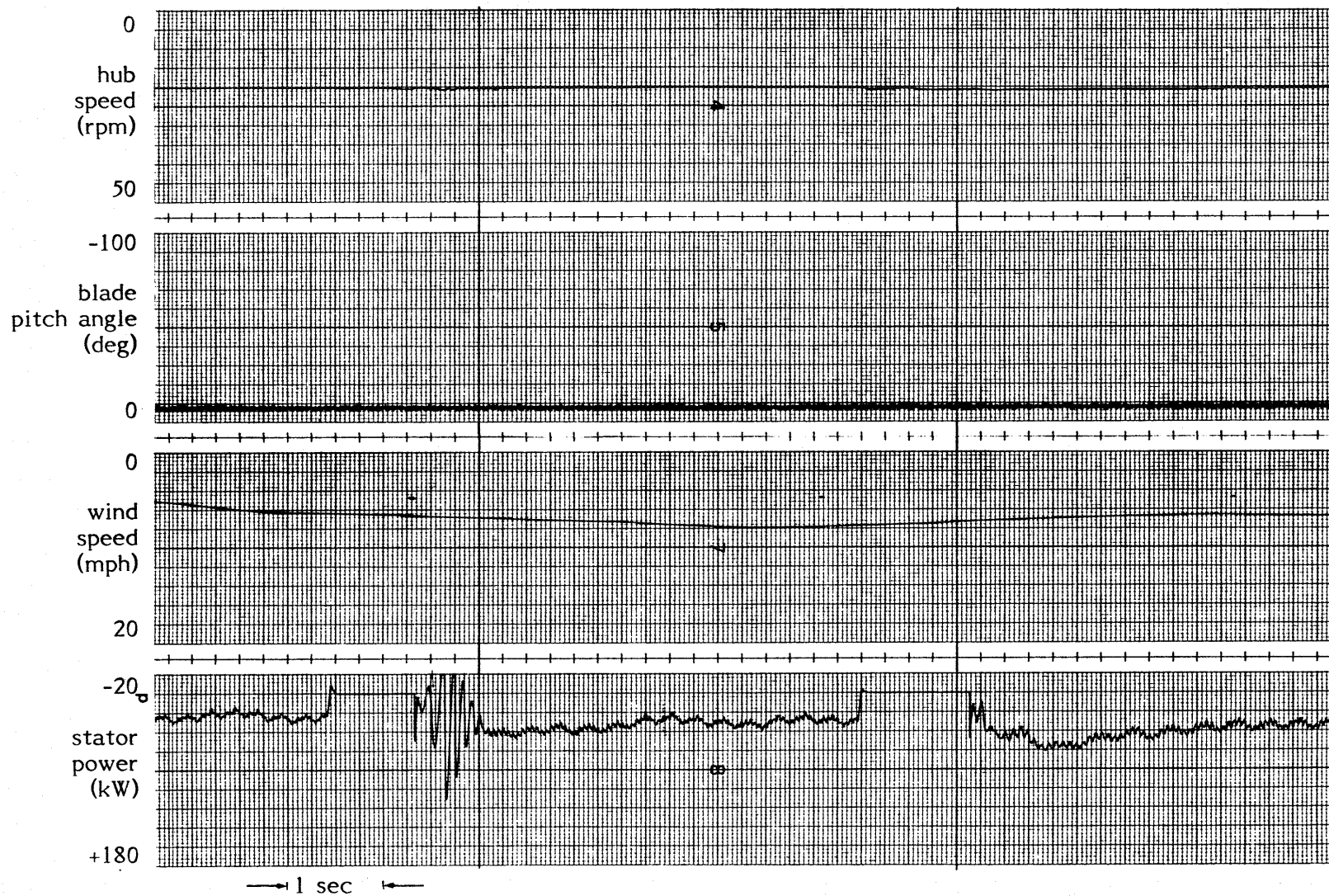


EXHIBIT 6.2 Loss of Output for 1.0 sec with VSCF System

Although the power oscillations due to excitation of the electrical mode die out more quickly for the induction generator case (see Exhibits 6.3 and 6.4), the system comes to an equilibrium point in just about the same time as required by the VSCF system. However, inrush currents of the induction generator are large and produce voltage dips that may affect certain types of loads, such as induction motors, connected near the WT. These results are consistent with simulation results presented in other work [6].

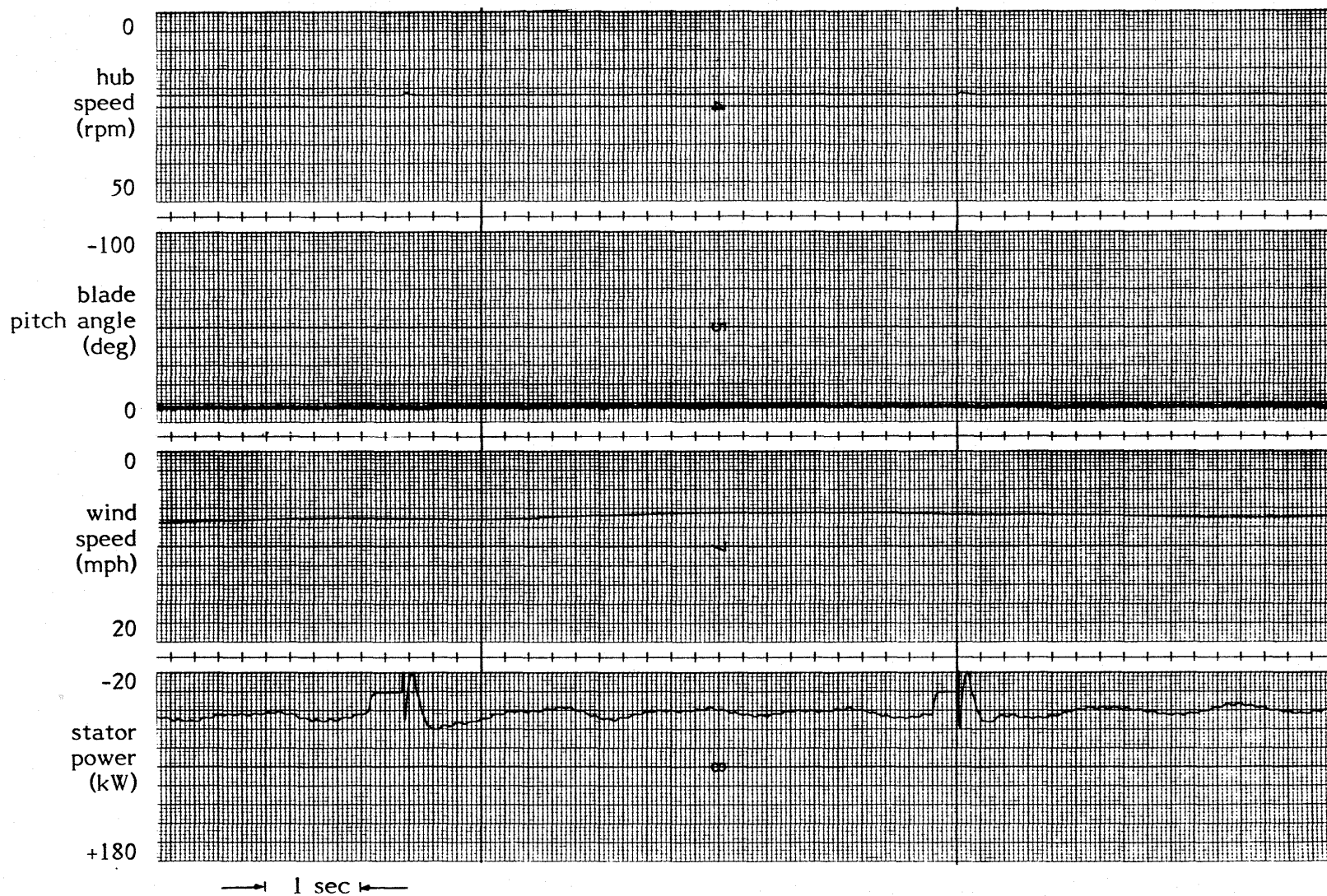


EXHIBIT 6.3 Loss of Output for 0.2 sec with Induction Generator



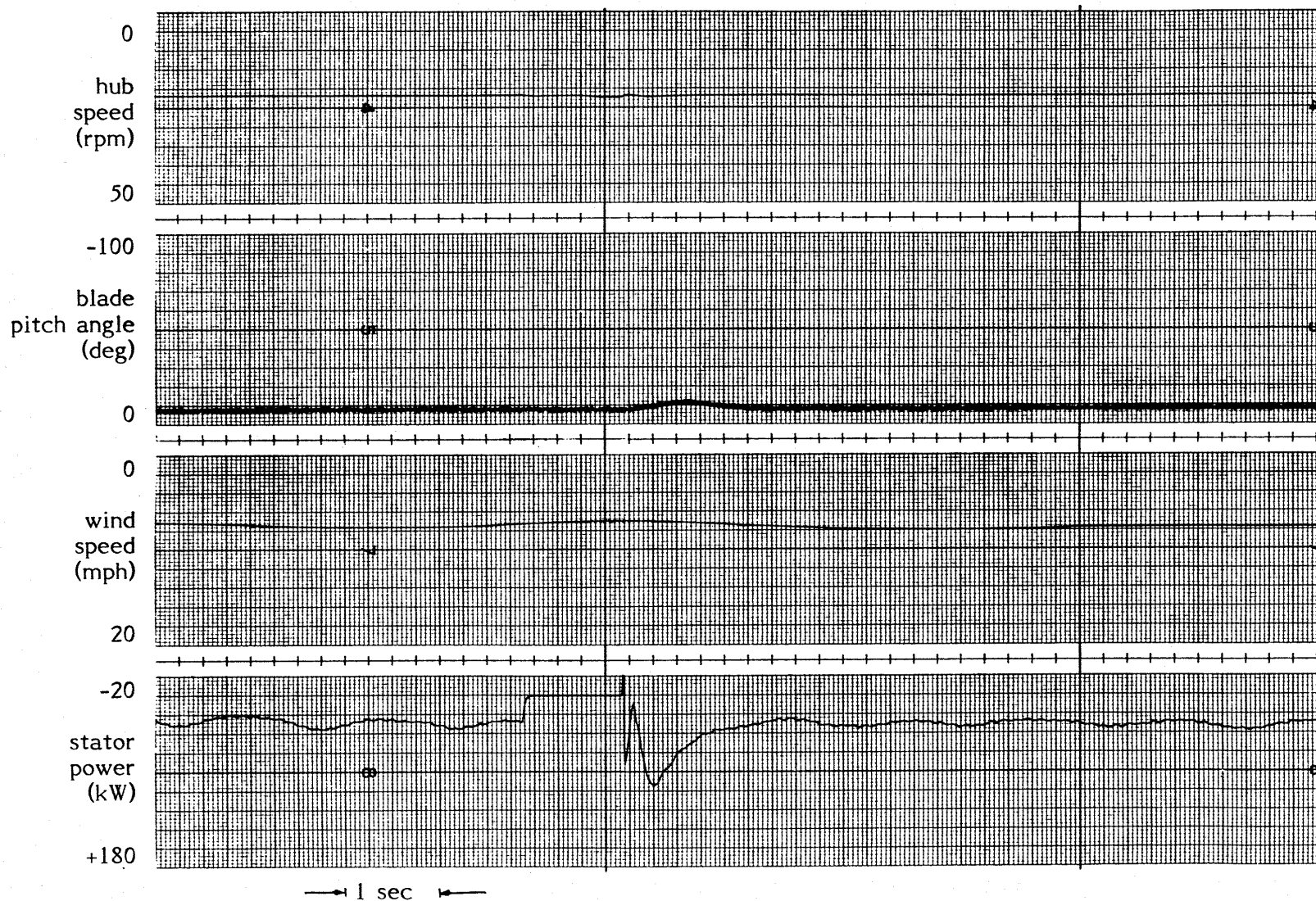


EXHIBIT 6.4 Loss of Output for 1 sec with Induction Generator



## 7.0 CONCLUSIONS

The behavior of the VSCF generating system has been analyzed from a utility perspective, i.e., a view of the machine from its terminals. Since the VSCF is an experimental system, the results obtained here should not be generalized to all variable speed constant frequency systems; rather, they should be viewed from the perspective of research in progress.

The power generated by the system has two predominant modes of oscillation: one that varies from 2p to 4p, and another mode that is associated with the slip frequency. The lower frequency oscillation seems to be induced by the 2p input, the generator rotor controller, or a combination of the two. In addition to this low frequency behavior, harmonic currents of 60Hz appear to be large, especially at generator speeds near synchronous, while harmonic voltages appear to be typical. Optimization of the rotor controller design will likely reduce these problems and improve the quality of the power delivered by the VSCF generator to the power system.

Although the generator rotor controller of the variable speed system behaves similarly to the excitation system of synchronous generators over a limited range in controlling the terminal voltage or the stator power factor, the VSCF system will always act as a net VAR sink. The primary reason is that the present configuration for the cycloconverter requires large amounts of reactive power. Since the power system has to supply this reactive power, the VSCF system appears as a reactive load to the utility. In order to use the VSCF system in a VAR dispatch mode, a supplementary capacitor would be

attached to the terminals of the generator to bias the level of reactive power supplied to the VSCF system. Then, reactive power control is used to provide VAR regulating capacity for the VSCF system. Such a configuration will permit the VSCF system to be an effective voltage/VAR management tool.

The ability of the built-in synchronizer to quickly adjust the phase angle and magnitude of the terminal voltage, in combination with the governor-like characteristics of the turbine controller, allowed resynchronization of the WT generator following a major electrical disturbance without requiring a shutdown/startup sequence procedure. This will reduce the downtime of wind electric production; therefore, the stability and reliability of the power system may actually be enhanced.

In summary, the VSCF system is shown to have a limited range of VAR control if coupled with supplementary capacitors. Further, the actual harmonic current production from the VSCF is rather significant and will require improvement in the generator rotor controller design to reduce the harmonic production levels. Power system stability and reliability are not significantly affected by the VSCF system.

## 8.0 REFERENCES

1. Brady, F.J., "Laboratory Testing of a 200-kW Variable-Speed Generating System," Proceedings of Horizontal-Axis Wind Turbine Technology Conference, May 8-10, 1984 (to be published).
2. Nyland, T.W. and Birchenough, A.G., Microprocessor Control System for 200-kilowatt Mod-OA Wind Turbines, DOE/NASA Report, DOE/NASA/20370-22, NASA TM-82711, January 1982.
3. McPherson, G., An Introduction to Electrical Machines and Transformers, John Wiley & Sons, 1981.
4. Hinrichsen, E.N., "Differences in Dynamic Behavior of Synchronous and Induction Machines in Wind Turbine Generators," Proceedings of the Fifth Biennial Wind Energy Conference and Workshop (WWV), Volume I, pp 407-412, October 1981.
5. Campen, G.L., Results of the Harmonics Measurement Program at the John F. Lono Photovoltaic House, Oak Ridge National Laboratory Report, ORNL-5834, March 1982.
6. Hinrichsen, E.N., Control of Large Wind Turbine Generators Connected to Utility Networks. DOE/NASA Report, DOE/NASA/0242-1, NASA CR-168200, May 1983.

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16. Abstract  <b>As efforts are accelerated to improve the overall capability and performance of wind-electric systems, increased attention to variable speed configurations has developed. A number of potentially viable configurations have emerged. Various attributes of variable speed systems need to be carefully tested to evaluate their performance from the utility point of view. With this purpose, the NASA, experimental variable speed constant frequency (VSCF) system based on a design by F. R. Schleif has been tested. In order to determine the usefulness of these systems in utility applications, tests are required to resolve issues fundamental to electric utility systems. Legitimate questions exist regarding how variable speed generators will influence the performance of electric utility systems; therefore, tests from a utility perspective, have been performed on the VSCF system and an induction generator at an operating power level of 30 kW on a system rated at 200 kVA and 0.8 power factor.</b>					
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